Control technique for single phase inverter photovoltaic system connected to the grid

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Abstract

In photovoltaic system connected to the grid, the main goal is to control the power that the inverter injects into the grid from the energy provided by the photovoltaic generator. The power quality injected into the grid and the performance of the converter system depend on the quality of the inverter current control. In this paper, a control technique for a photovoltaic system connected to the grid based on digital pulse-width modulation (DSPWM) which can synchronize a sinusoidal output current with a grid voltage and control the power factor is proposed. This control is based on the single phase inverter controlled by bipolar PWM Switching and lineal current control. The electrical scheme of the system is presented. The approach is widely explained. Simulations results of output voltage and current validate the impact of this method to determinate the appropriate control of the system. A digital design of the control based on generator PWM using VHDL is proposed and implemented on Field-Programmable Gate Array "FPGA".

The functional structure of this system with digital control has been validated with experimental results.

1. Introduction

The penetration of renewable energy sources is increasing exponentially due to power and digital electronics. Renewable energy sources are connected to the grid through power converters which besides transferring the generated dc power to the ac grid. The grid connected Photovoltaic (PV) systems are essentially composed of arrays of PV modules, connected to the grid through an power conditioning system includes a DC/AC converter, the Maximum power point Tracker MPPT, the filter and the control systems needed for performing efficient system operation.

The control tasks can be divided into two major parts [1–5].
(1) The controller on the PV modules side, is used in order to extract the maximum power from the PV modules.

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(2) The controller on the grid side, is used in order to control both active and reactive power supplied to the grid; • control of dc-bus; • guarantee high quality of the injected power; • grid synchronization [6–8], [5], [9–12].

For lower installation of photovoltaic systems connected to the grid, pulse width modulation (PWM) is a widely used technique for controlling the voltage source inverters injects currents into the grid. The current injected must be sinusoidal with reduced harmonic distortion. Moreover, a sinusoidal input current should be achieved with a total harmonic distortion (THD) below 5% as suggests the international standard IEEE std 929 — 2000.

The main objective of the current controller is to ensure that the output inverter current follow carefully the reference current independently of the selected control technique. The current controller of power converters can be a closed loop PWM, such as Hysteresis Current Control, linear PWM, predictive controllers, optimized controllers, neural network and fuzzy logic controller systems [4]. In comparison to open loop, PWM techniques, have several considerable advantages, such as extremely good dynamics, instantaneous peak current control and prevention of overload and pulse dropping problems.

For grid connected photovoltaic single phase inverter; there are two common switching strategies, which are applied to the inverter; these are Bipolar and Unipolar PWM switching. The PWM technique could be utilized for controlling the inverter's voltage source that injects currents into the grid. Many PWM procedures can be adopted [11]. Generally the PWM technique comprises a compare of the high frequency which represents the triangular carrier signal with a low frequency signal (the sinusoidal reference waveform).

The control strategy in [9] use the digital unipolar DPWM patterns to control the injected current in phase with the grid voltage. In [13] the control is based on using digital unipolar DPWM patterns for different modulation index m_a and the phase shift angle of the inverter output voltage as control parameter. This control strategy allow the control of power injected into the grid. The output current amplitude and the power factor can be controlled, changing the power factor; the injected inductive or capacitive reactive power can be dynamically changed and controlled.

Digital implementation of the control provides improvements over their analogue one. Immunity to the noise and insensitiveness in the changes of voltage and temperature. Field-Programmable Gate Array (FPGA's) implementation give suppleness in changing the designed circuit, easy and fast circuit modification without modifying the hardware and rapid prototyping [7,13].

In this work, the proposed control is based on digital bipolar PWM Switching which reduce the magnitude of the low order of harmonic components existing in the input AC supply in order to improve the output power quality of grid connected PV inverters and lower equipment costs for these systems. This will be achieved through H-bridge inverter and digital current control based on sinusoidal pulse width modulation and feed-forward technique, for achieving an inverter with advanced accuracy and reliability.

In this paper, a detailed description of the proposed control strategy of the photovoltaic system connected to the grid based on the lineal current control is presented. The control has been implemented in FPGA.

Digital implementation of the control is provided. Finally simulations and experimental results are presented and discussed.

2. PV system connected to the grid

Fig. 1 shows an electrical scheme of the single phase inverter connected to the grid [1,2]. The main specification of the inverter connected to the grid is that the current must be injected from a PV panel with a power factor within a certain range [1]. DC/DC converter is employed to boost the PV-array voltage to an appropriate level based on the magnitude of utility voltage, while the controller of the DC–DC converter is designed to operate as a maximum power point tracker (MPPT) that increases the economical feasibility of the PV system. The performance of the PV inverters is mainly characterized by means of their efficiency. However, the total efficiency includes conversion and MPP-tracking efficiency. The MPPT performance is a very significant aspect of the characterization of PV inverters since the PV systems must extract the maximum energy available from PV generator all time. So, the global efficiency of the MPPT algorithms depends on its ability to make the inverter operate at the maximum power point (MPP) at every moment. In order to do it, the MPPT algorithm has to track accurately the variations of the MPP, which can be changed by factors such as irradiance and temperature variations and partial shading processes. Obviously, this accuracy will be strongly influenced by both the amplitude and the dynamics of the variations of the MPP. In the PV grid-connected systems, the algorithms of MPPT-tracking are implemented in all
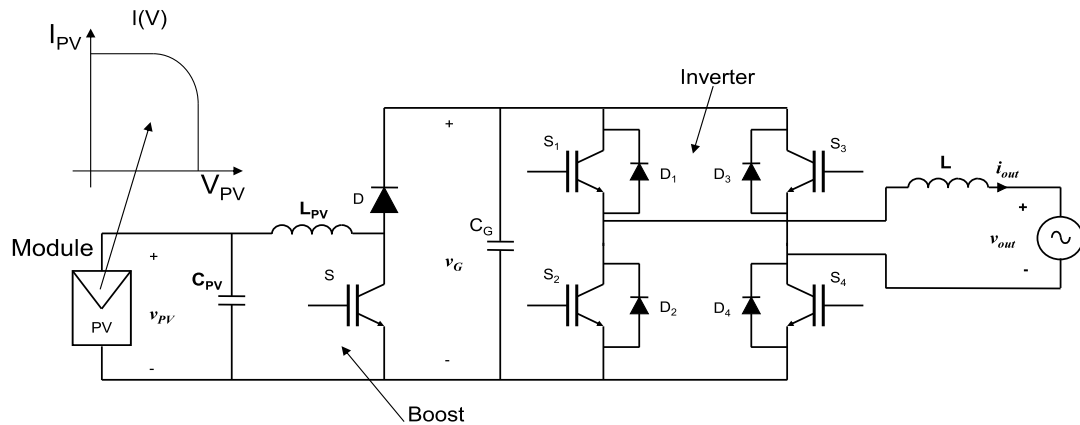
Fig. 1. Grid connected photovoltaic system.

PV inverters. A large variety of MPP tracking algorithms exists look-up table, perturbation and observation (P&O), incremental conductance etc. [14,15].

For the MPPT controller, the perturb-and-observe method is adopted owing to its simple structure and the fact that it requires fewer measured parameters. This strategy is implemented to operate under rapidly changing solar radiation in a power PV grid connected System.

The DC–AC converters inject sinusoidal current into the grid controlling the power factor. Therefore, the inverter converts the DC power from the PV generator into AC power for grid injection. One important part of the system PV connected to the grid is its control. The control can be divided into two important parts.

(1) MPP controller, with the main property to extract the maximum power from the input source (PV module).

(2) Inverter controller, which ensure the control of active and reactive power generated to the grid; the control of dc-link voltage; high quality of the injected power and grid synchronization.

3. Inverter control

The control structure that has been implemented for the single-phase inverter is shown in Fig. 2. The photovoltaic system consists in photovoltaic generator (PVG), a maximum power point tracking (MPPT) and the inverter.
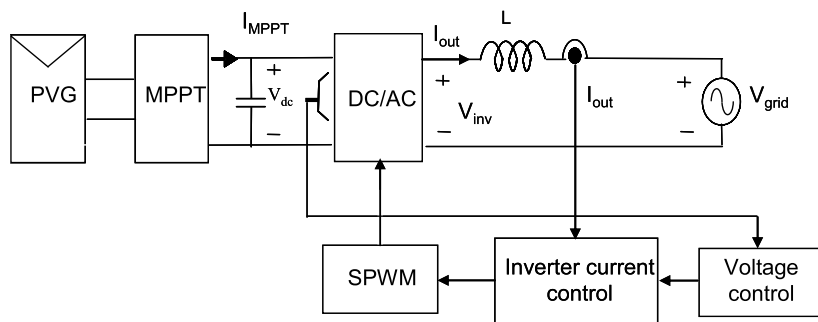

Fig. 2. Control structure diagram [9].

The control structure proposed for the single-phase inverter corresponds to 2 control loops as shown in Fig. 3.

- An external control loop of the DC voltage is necessary to maintain the DC-bus voltage constant to guarantee the correct function of the MPPT.
- An internal control loop of the current is designed to control the power injected into the grid. This allows the output current control in instantaneous values. To impose a sinusoidal current, in phase with the grid voltage, the reference current I_{ref}, is generated from a sinusoidal reference, the amplitude is regulated from the output of the external voltage loop.
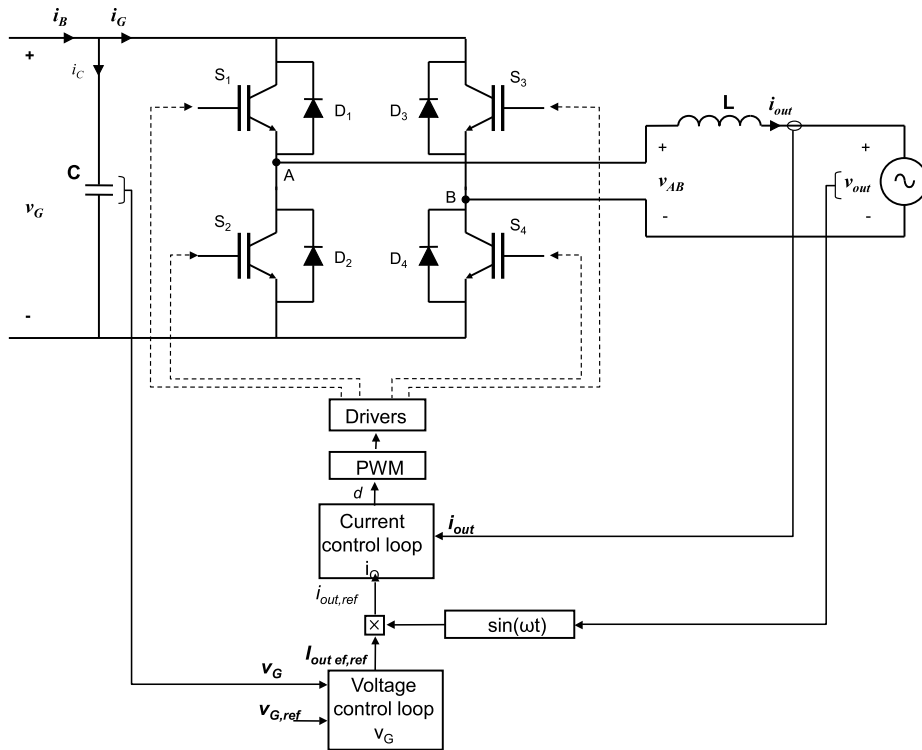
Fig. 3. Control of the inverter connected to the grid.

One of the advantages provided by this control strategy is its simplicity as far as the computational requirements of the control circuit.

The DC-bus voltage of the PV system is maintained constant such that active power balance between the injecting solar energy and the system output power can be achieved. The DC-bus voltage V_{dc}, can be feedback and compared with the desired value of V_{dc} (ref) while a PI regulator is added to regulate the error between the desired voltage and the actual DC bus voltage, hence the reference current signal can be obtained. The current regulator is employed to regulate the error between the desired current and actual output current Fig. 4 [1].
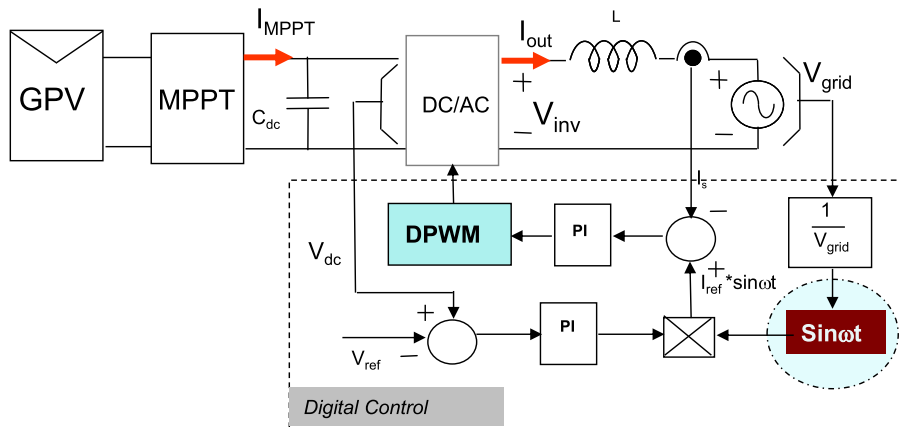

Fig. 4. Control structure of the inverter connected to the grid.

This structure is associated with proportional integral controllers (PI). To improve the performance of the PI controller in such a current control structure and to cancel the voltage ripples of the photovoltaic generator, due

to variations in the instantaneous power flow through the photovoltaic system, will depend on the change of atmospheric conditions (mainly the irradiance and temperature), the faster response of the boost control loop, the inverter and the value of the DC bus capacitor. On the other hand, the output voltage (the mains voltage) represents an external disturbance of considerable magnitude at 50 Hz for the system.

There exists a compensation of these effects at the output of the PI controller so as to calculate directly the reference voltage for the inductance. Fig. 5 shows the control loop of the inverter output current [1].
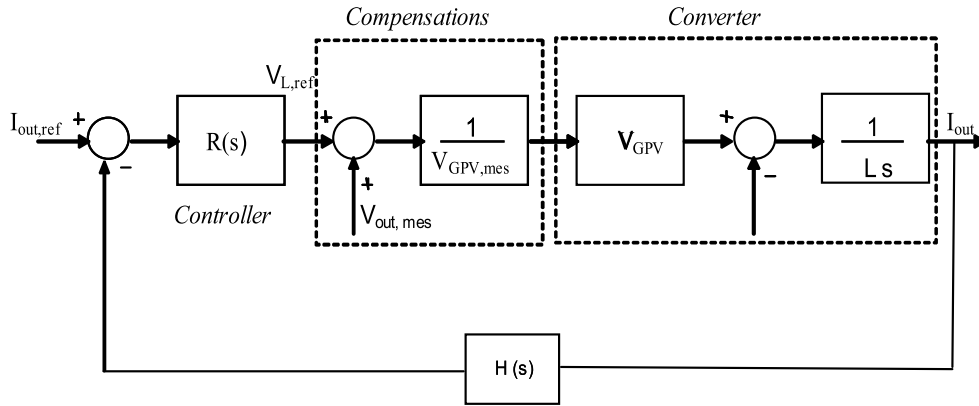

Fig. 5. Output current control loop structure.

The inverter output current expression is given [1]:

$$I_{out}(s) = \frac{D \cdot V_{GPV}(s) - V_{out}(s)}{Ls} \tag{1}$$

The feed-forward technique is based on including new terms to variables control, in this case the duty cycle, in order to eliminate the dependence related to the perturbations of control system.

To compensate the effect of output voltage, the average and filtered output voltage values, called $v_{out, mes}$, are used Fig. 4. However, to compensate the voltage v_{Gpv}, it is necessary to use, the measured value before filtered.

In this case, it is necessary to calculate a duty cycle since the transfers' functions:

$$d = \frac{v_{L,ref} + v_{out,mes}}{v_{GPV,mes}} \tag{2}$$

Ksv the same step of measured circuits, obtained:

$$d = \frac{v_{L,ref} + K_{sv}v_{out}}{K_{sv}v_{GPV}} \tag{3}$$

From the duty cycle, the inductance voltage V_L can be deduced:

$$v_L = dv_{GPV} - v_{out} = \frac{v_{L,ref}}{K_{sv}} \tag{4}$$

The advantage of this control structure is the control of the instantaneous power injected into the grid from the solar module and the synchronization of the current signal with the grid voltage which guarantee a higher power factor and improve the MPPT dynamic. The disadvantage is the noise in the inverter output current signal due to the use of the grid signal sample for generating and synchronizing the reference current with the grid signal.

4. Digital implementation

The Digital Pulse-Width-Modulator (DPWM) converts the code in pulsating signal and generates the driving signals of the switches. Fig. 6. shows the digital implementation of the bipolar PWM. The switching frequency is 10 kH in order to reduce harmonics
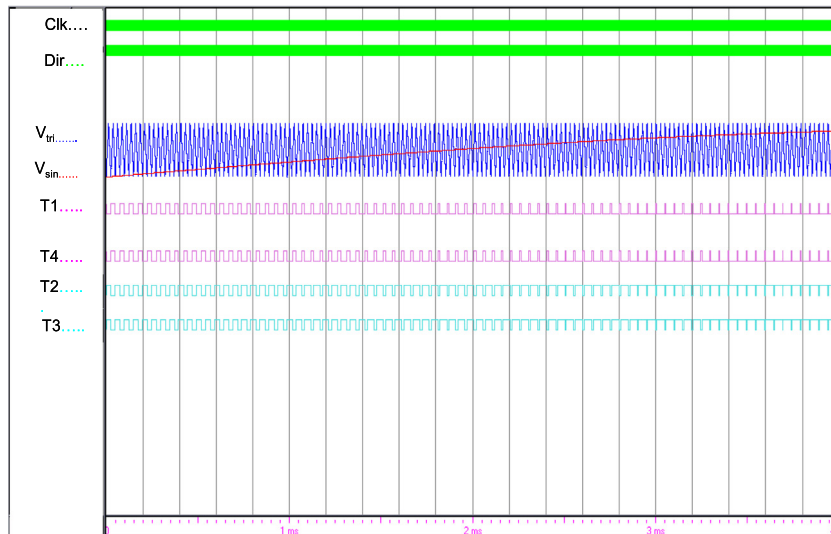
Fig. 6. DPWM signals.

5. Simulation results

The photovoltaic generator (PVG), the maximum power point (MPPT) and the single-phase inverter DC/AC behavior have been modeled and simulated by PSIM as shown in Fig. 7. The simulation parameters used are: voltage V_{grid} 230 V, frequency 50 Hz, L = 4.7 mH, V_{dc} = 375 V and frequency modulation index m_f = 200.
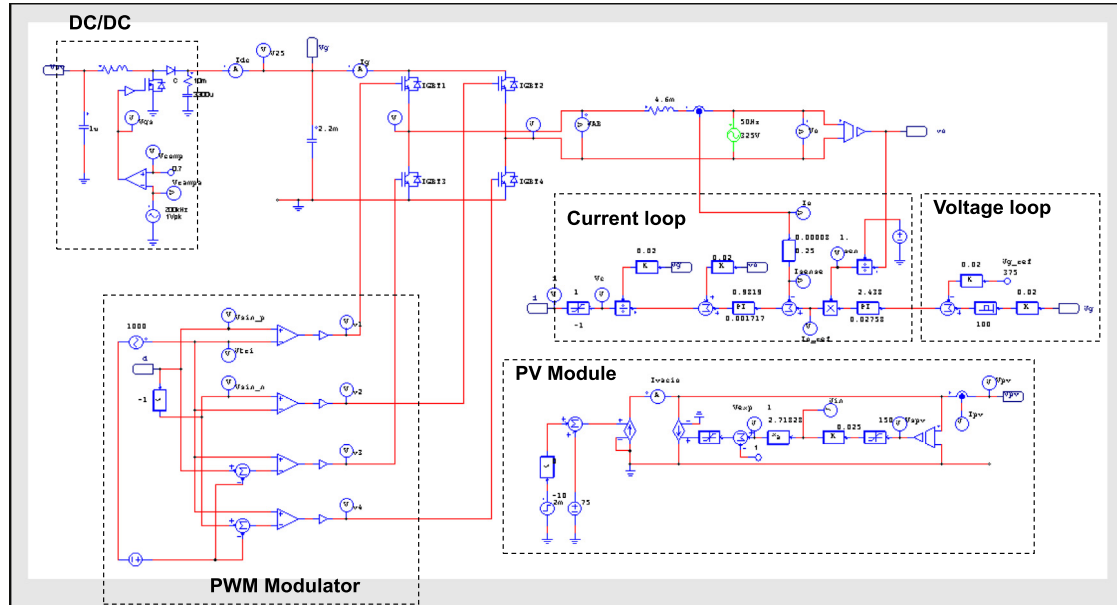

Fig. 7. Model of the inverter connected to the grid.

Simulation results of the photovoltaic system connected to the grid are presented in Fig. 8. Is shown the DC bus V_{dc} constant; the measured output current I_{mes}, and the reference output current $I_{ref.}$.

The external control loop of the DC voltage maintain the DC-bus voltage constant to guarantee the correct function of the MPPT. The reference current I_{ref}, is generated from a sinusoidal reference, the amplitude is regulated from the output of the external voltage loop.
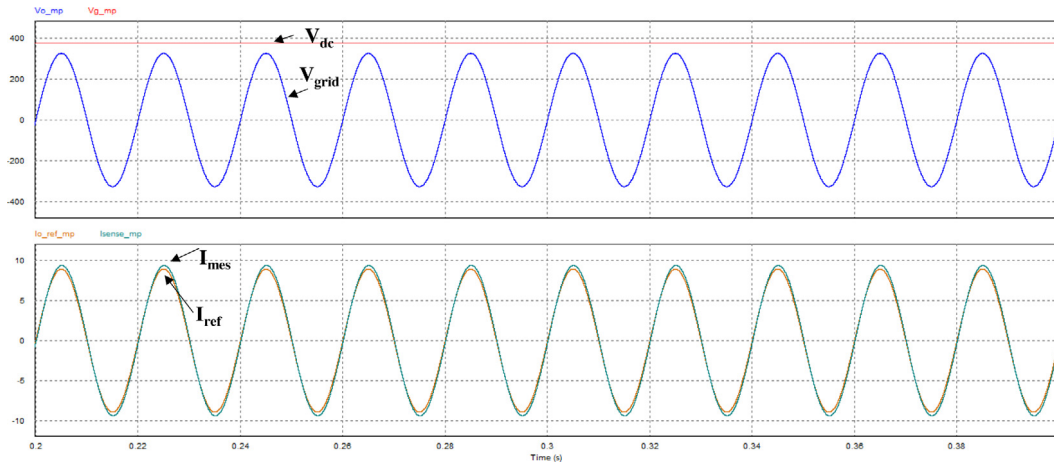
Fig. 8. DC voltage, inverter measured output current and reference output current.

Fig. 9 illustrates the inverter output voltage V_{inv}, the measured output current I_{mes}, the reference output current I_{ref} of the inverter and the duty cycle d. The measured output current I_{mes} follows correctly the reference output current $I_{ref.}$. the error between I_{mes} and $I_{ref.\approx0}$.
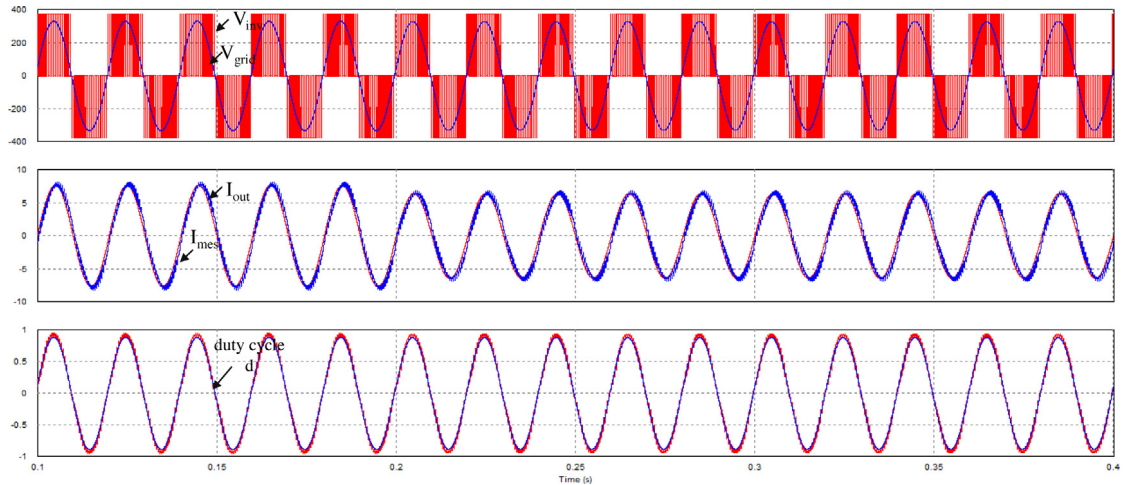

Fig. 9. Inverter output voltage, grid voltage, inverter measured output current and reference current.

Fig. 10 shows simulation results in the open loop and closed loop of the inverter output current I_{out} with the grid voltage V_{grid}. The internal control loop of the current control the power injected into the grid and the output current in instantaneous values to impose a sinusoidal current, in phase with the grid voltage.

6. Experimental results

A prototype of single-phase inverter with the digital control implemented in a FPGA platform (Spartan-3E of Xilinx) realized and tested. $V_{grid} = 230$ V, and coupling inductance L $= 4.6$ mH. Experimental results are presented Figs. 11 and 12 .

Fig. 11 shows the experimental results of bipolar DPWM signals, Fig. 12(a) demonstrates the bipolar inverter output signal and inverter output current. In Fig. 12(b) illustrates the inverter output current and the grid emulator voltage.
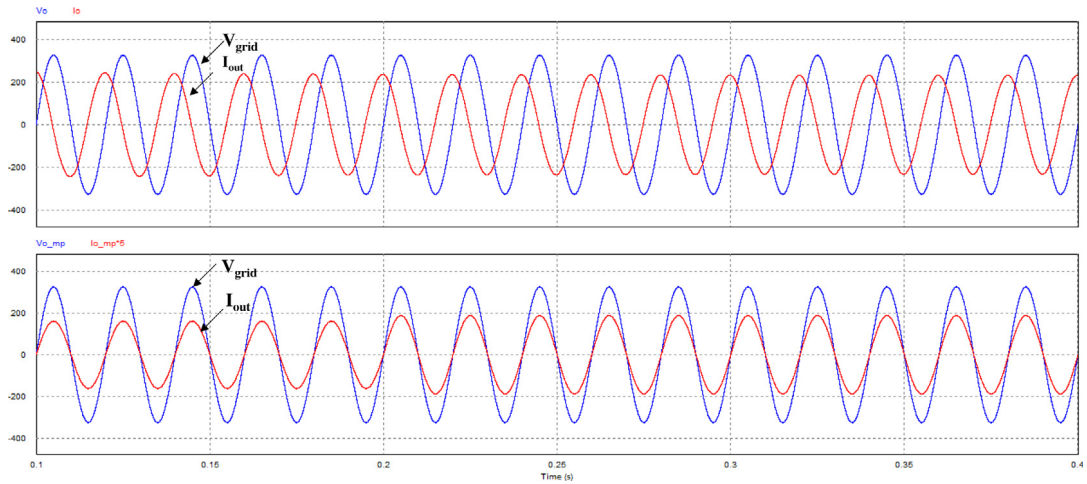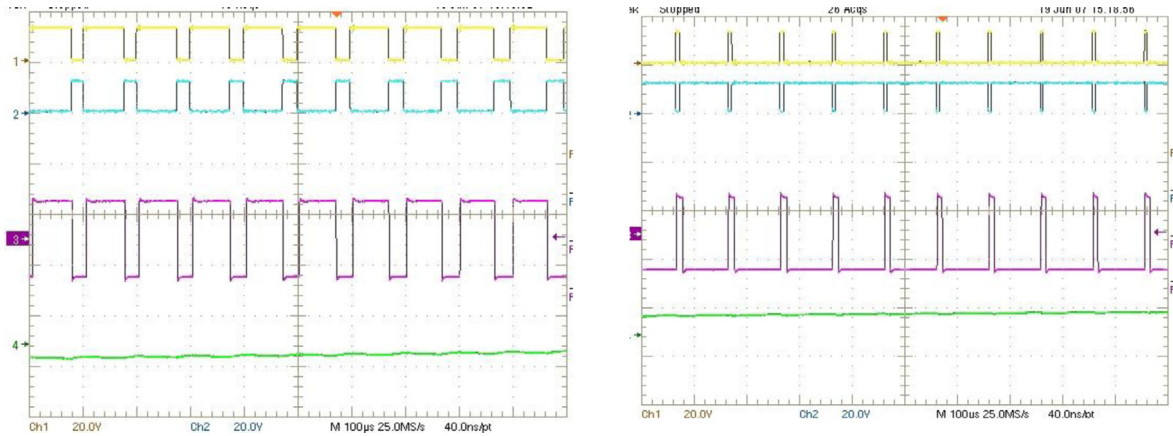
Fig. 10. Inverter output current and grid voltage.

Fig. 11. Bipolar DPWM Signals.

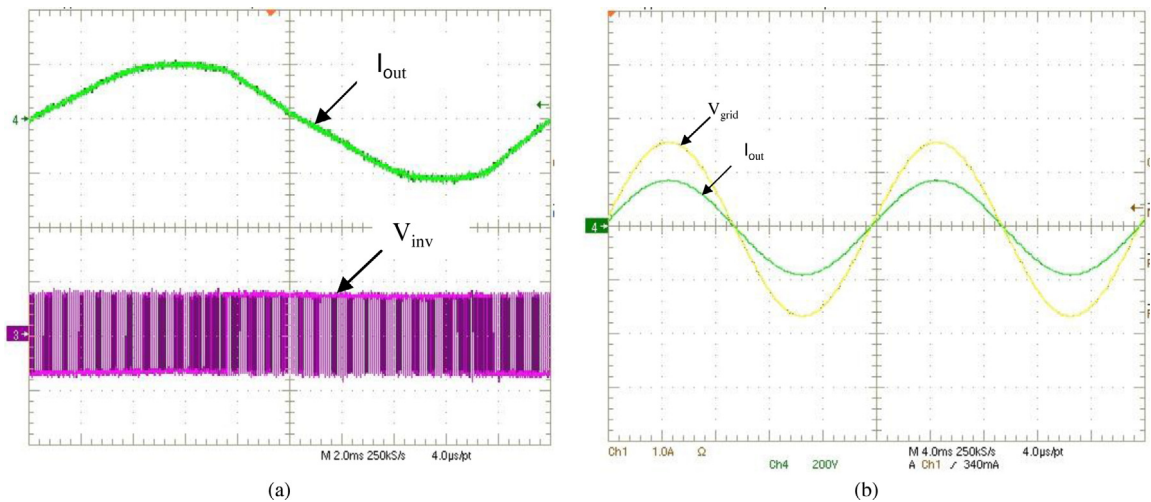(a)   (b)

Fig. 12. Bipolar inverter output signal and inverter output current (a), Inverter output current and grid voltage (b).

7. Conclusions

In this paper the design of a digital control system of the single phase inverter connected to the grid has been developed that can improve the efficiency of the photovoltaic systems. The model of the control system based on the DSPWM and feed forward technique has been designed and simulated. The simulation and experimental results validate the theoretical predictions and demonstrate the viability of the proposed control. The digital current control shows the capability of the proposed SPWM method and the simplicity of the digital implementation.

This technique confirm that the control can be applied to control the power and the current injected into the grid. Using Xilinx FPGA to generate PWM provides flexibility to modify the designed circuit without altering the hardware part. This system can improve the power quality output of grid connected PV inverters and lower equipment costs for these systems.

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